Frequency-dependent reflection of spin waves from a magnetic inhomogeneity induced by a surface DC-current

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The reflectivity of a highly localized magnetic inhomogeneity is experimentally studied. The inhomogeneity is created by a dc-current carrying wire placed on the surface of a ferrite film. The reflection of propagating dipole-dominated spin-wave pulses is found to be strongly dependent on the spin-wave frequency if the current locally increases the magnetic field. In the opposite case the frequency dependence is negligible.

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The interaction of spin-wave packets propagating in a ferromagnetic film with localized artificial inhomogeneities is of interest for numerous applications. For example, the tunneling [1], the guidance [2], the filtering through band gaps [3], and shaping [4] of spin-wave pulses has been realized in this way.

There are different possibilities to create inhomogeneities, such as by mechanical structuring of the magnetic material [3, 5, 6] or by variation of the saturation magnetization by ion irradiation [7]. However, these modifications of the magnetic properties are irreversible and do not allow any adjustment or real-time control.

A more promising approach is to change the magnetic inhomogeneity dynamically as can be done e.g. with parametric pumping by fast variation of the bias magnetic field [4, 8]. In this process the increase of the precessing transversal magnetization component leads to a decrease of the static saturation magnetization. However, one should keep in mind the high complexity of the process and the relatively long time scale in the microsecond range to reach a quasi-equilibrium regime [9, 10].

Instead, many recent experiments [11, 12, 13] have relied on the technique to locally modify the bias magnetic field by the Oersted field of a current-carrying wire placed on the film surface. With this setup, XOR and NAND gates, milestones in the development of spin-wave logic, have been realized [14] and resonant spin-wave tunneling has been discovered [15]. Moreover, periodic structures, so called magnonic crystals, of such design [16] have the advantage of being controllable on a time scale shorter than the spin-wave relaxation time.

In the current work, we directly measure the reflected and transmitted intensity of spin-wave pulses propagating in a thin yttrium-iron-garnet (YIG) film through a current induced magnetic inhomogeneity for a wide range of spin-wave carrier frequencies and applied dc-currents. The results provide evidence for the potential of this structure as an effective frequency filter and adjustable energy divider.

All experiments were performed in the pulse regime. This approach was chosen to check the applicability of the method for microwave signal processing used in modern digital technique and exclude any influence of heating effects caused by the dc-current applied to the wire.

Figure 1(a) shows a sketch of the experimental setup. A triggered microwave switch transforms the cw-signal of a microwave generator with a carrier frequency f between 7.010 GHz and 7.115 GHz into 280 ns long pulses with a 1 ms repetition rate. These pulses are sent to a 50 μm wide strip-line transducer placed on the surface

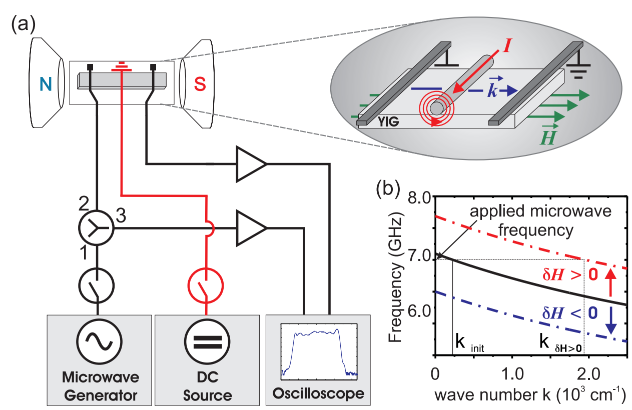

FIG. 1: (Color online) (a) Sketch of the experimental microwave setup and of the section layout. (b) Schematic representation of the dc-current influence on the dispersion relation.

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of a 5 μm thick, longitudinally magnetized single crystal YIG-stripe of 15 mm width.

The microwave signal excites packets of backward volume magnetostatic waves (BVMSW) whose wave vector is aligned in the direction of the applied bias magnetic field $H = 1800$ Oe with a typical value between 10 cm^{-1} and 200 cm^{-1}. The spin waves propagate through the film and are picked up by a second, identical antenna situated at a distance of 8 mm. By amplifying and detecting the obtained microwave signal we can observe the transmitted pulse in real time.

While the spin-wave pulse is propagating in the film a 180 ns long and between -2 A and $+2$ A strong dc-current pulse with a rise time of less than 20 ns is applied to a 50 μm thick wire placed on the film surface halfway between the antennae (Fig. 1(a)). It creates a highly localized magnetic inhomogeneity across the YIG-waveguide of up to ± 200 Oe and width comparable to the spin-wave wavelength. The length of the dc-current pulse is chosen in order to, on the one hand, avoid heating the sample and, on the other hand, reach a stationary state of the spin-wave propagation. For such a structure, two principally different operation regimes exist (Fig. 1(b)). If the dc-current locally decreases the bias magnetic field we operate in the *tunneling regime* [1]. We will refer to the opposite case as *diffraction regime*.

Spin waves reflected from the inhomogeneity are picked up by the input antenna. A Y-circulator in the input channel allows to detect and observe this signal on the oscilloscope simultaneously to the transmitted one.

In Fig. 2(a) the transmission and reflection characteristics for exemplary currents -0.5 A and -1.0 A representative for the tunneling regime as well as $+0.5$ A and $+1.0$ A for the diffraction regime are shown together with the characteristics obtained when no current is applied.

If no current is applied the measured intensities are determined by the excitation and detection characteristics of the used microstrip antennae and the spin-wave spectrum. Because of the finite size of the antennae, the excitation and detection is limited to spin waves with a long enough wavelength. This explains the vanishing intensity for frequencies below 7.02 GHz. At the same time, the frequency of ferromagnetic resonance $f_{\rm FMR} \approx 7.10$ GHz constitutes an upper frequency limit for the BVMSW in the dipole approximation. Hence, the intensity of the detected signal quickly drops above it. Note, that in the absence of a current, only a relatively small part of the spin wave is reflected by the metal wire placed on the sample surface [17], so that most of the spin-wave signal is observed in transmission. The dips observable in the reflected and transmitted signal are caused by resonances between the input antenna and the central wire.

When a dc-current is applied, the ratio between reflection and transmission changes significantly depending on the direction and magnitude of the applied dc-current. In the tunneling regime, i.e. when the bias magnetic field is locally decreased by the current, the reflected signal monotonically increases over the whole investigated

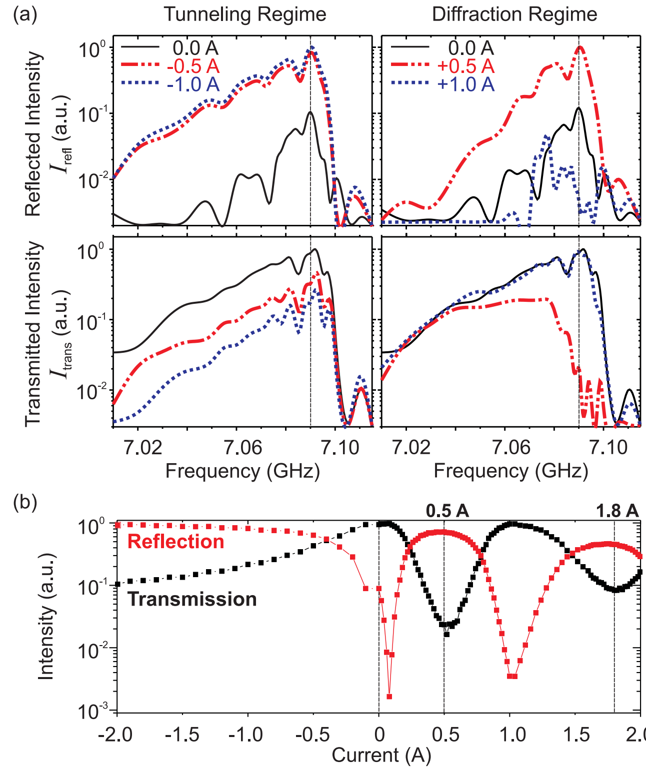

FIG. 2: (Color online) (a) Reflection and transmission characteristics in the tunneling and diffraction regime. The vertical dashed line indicates $f = 7.09$ GHz. (b) Current dependent reflection and transmission for $f = 7.09$ GHz.

frequency range with increasing current modulus. In the diffraction regime the behavior is non-monotonous. When the current is increased two reflection resonances are clearly observed. They are most pronounced for $f = 7.09$ GHz, which is slightly below $f_{\rm FMR}$ (see Fig. 2).

For 0.5 A the reflected signal intensity increases drastically compared to the case without current. The reflected signal rises within 30 ns after the application of the dc-pulse by a factor of 10. The intensity then stays constant for the remainder of the microwave signal pulse.

Further increase of the current leads to a decrease of the reflected signal intensity. At a current of 1.0 A the reflected signal is effectively suppressed and the transmitted pulse shape is almost undisturbed. This behavior is repeated when the current is further increased. The reflected spin-wave intensity rises till it reaches a second maximum at 1.8 A and then drops again. Fig. 2(b) displays the current dependence of the reflected and transmitted signal intensity for $f = 7.09$ GHz.

By adding the reflected and transmitted signal intensities, it can be verified that their sum stays constant.

To explain the two different regimes, consider Fig. 1(b) again. In the tunneling regime, for large enough current modulus a barrier is formed which reflects the signal. A larger absolute current leads to an increase of the zone where the spin-wave propagation is prohibited and through which, consequently, the spin waves can-

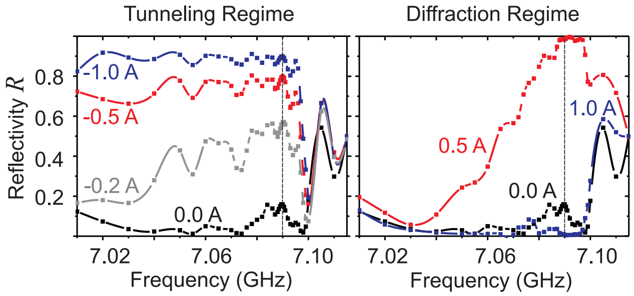

FIG. 3: (Color online) Frequency-dependent reflectivity.

not propagate and need to tunnel [1]. In the diffraction regime, constructive interference of spin waves reflected from the region of inhomogeneous magnetic field occurs. The observed data on spin-wave reflection supports very well the theoretical prediction reported in [11] by the authors.

We determine the frequency-dependent reflectivity R of the investigated structure via

$$R = \frac{I_{\text{refl}}}{I_{\text{trans}} + I_{\text{refl}}}$$

where I_{refl} and I_{refl} denote the reflected respectively transmitted intensity (Fig. 3). In the tunneling regime, for large enough currents the reflectivity is constant over the whole range of accessible frequencies. The picture is completely different in the diffraction regime. Here, the reflectivity is clearly frequency-dependent. For low frequencies between 7.01 GHz and 7.04 GHz it is constant and restricted to $R < 0.2$. For higher frequencies which are closer to f_{FMR}, a strong dc-current dependence is observed. In particular, we note that the reflectivity for $f = 7.09$ GHz and $I = -0.5$ A is only 0.78 while it reaches almost 1 for the opposite dc-current polarity.

In conclusion, we have investigated the reflection of dipole-dominated spin waves propagating through a highly localized dc-current induced magnetic inhomogeneity. The reflection on the inhomogeneity created by a surface dc-current proves to be dependent on the frequency of the propagating spin wave as well as on the magnitude and polarity of the dc-current. While the latter two dependencies are monotonous for a current decreasing the local magnetic field (*tunneling regime*) they exhibit a resonant structure in the opposite case (*diffraction regime*) which is well pronounced only in a small frequency range below f_{FMR}. For a given current of 0.5 A the ratio of transmitted signals in tunneling and diffraction operation regime is more than 25.

These results have to be considered for the future design of current controlled spin-wave devices, e.g. spin-wave logic gates and dynamic magnonic crystals. While the diffraction regime has the advantage of a high reflectivity for relatively low and easily reachable currents (which allow for long current pulses without disturbing heating effects), the tunneling regime allows the design of frequency-independent structure. This may be especially interesting for ultra-short pulses with a wide Fourier spectrum. In addition, the frequency-dependent reflection in the diffraction regime can be used to create tunable frequency selective devices. By using multiple wires instead of just a single one, the characteristics of the structure can be further improved.

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[1] S. O. Demokritov, A. A. Serga, A. André, V. E. Demidov, M. P. Kostylev, and B. Hillebrands, Phys. Rev. Lett. **93**, 047201 (2004).

[2] J. Topp, J. Podbielski, D. Heitmann, and D. Grundler, Phys. Rev. B **78**, 024431 (2008).

[3] A. V. Chumak, A. A.Serga, B. Hillebrands, and M. P. Kostylev, Appl. Phys. Lett. **93**, 022508 (2008).

[4] A. A. Serga, T. Schneider, B. Hillebrands, M. P. Kostylev, and A. N. Slavin, Appl. Phys. Lett. **90**, 022502 (2007).

[5] A. Maeda, and M. Susaki, IEEE Trans. Magn. **42**, 3096 (2006).

[6] M. P. Kostylev, P. Schrader, R. L. Stamps, G. Gubbiotti, G. Carlotti, A. O. Adeyeye, S. Goolaup, and N. Singh, Appl. Phys. Lett. **92**, 132504 (2008).

[7] R. L. Carter, J. M. Owens, C.V. Smith, and K.W. Reed, J. Appl. Phys. **53**, 2655 (1982).

[8] G. A. Melkov, A. A. Serga, A. N. Slavin, V. S. Tiberkevich, A. N. Oleinik, and A. V. Bagada, JETP **89**, 1189 (1999).

[9] V. E. Demidov, O. Dzyapko, S. O. Demokritov, G. A. Melkov, and A. N. Slavin, Phys. Rev. Lett. **99**, 037205 (2007).

[10] T. Neumann, A. A. Serga, and B. Hillebrands, submitted, arXiv:0810.4033v1 [cond-mat.other] (preprint).

[11] M. P. Kostylev, A. A. Serga, T. Schneider, T. Neumann, B. Leven, B. Hillebrands, and R. L. Stamps, Phys. Rev. B **76**, 184419 (2007).

[12] V. E. Demidov, U. H. Hansen, and S. O. Demokritov, Phys. Rev. B **78**, 054410 (2008).

[13] K. R. Smith, M. J. Kabatek, P. Krivosik, and M. Wu, J. Appl. Phys. **104**, 043911 (2008).

[14] T. Schneider, A. A. Serga, B. Leven, B. Hillebrands, R. L. Stamps, and M. P.Kostylev, Appl. Phys. Lett. **92**, 022505 (2008).

[15] U. Hansen, M. Gatzen, V. E. Demidov, and S. O. Demokritov, Phys. Rev. Lett. **99**, 127204 (2007).

[16] Y. K. Fetisov, J. Comm. Tech. Electron. **10**, 1171 (2004).

[17] I. V. Krutsenko, G. A. Melkov, and S. A. Ukhanov, Radiotexn. i Elektron. **32**, 1976 (1987).